Nanotechnology Infrared Optics for Astronomy Missions

Grant NAG5-9363

Annual Performance Report No. 3

For the period 1 April 2002 through 31 March 2003

Principal Investigator:

Dr. Howard A. Smith

February 2003

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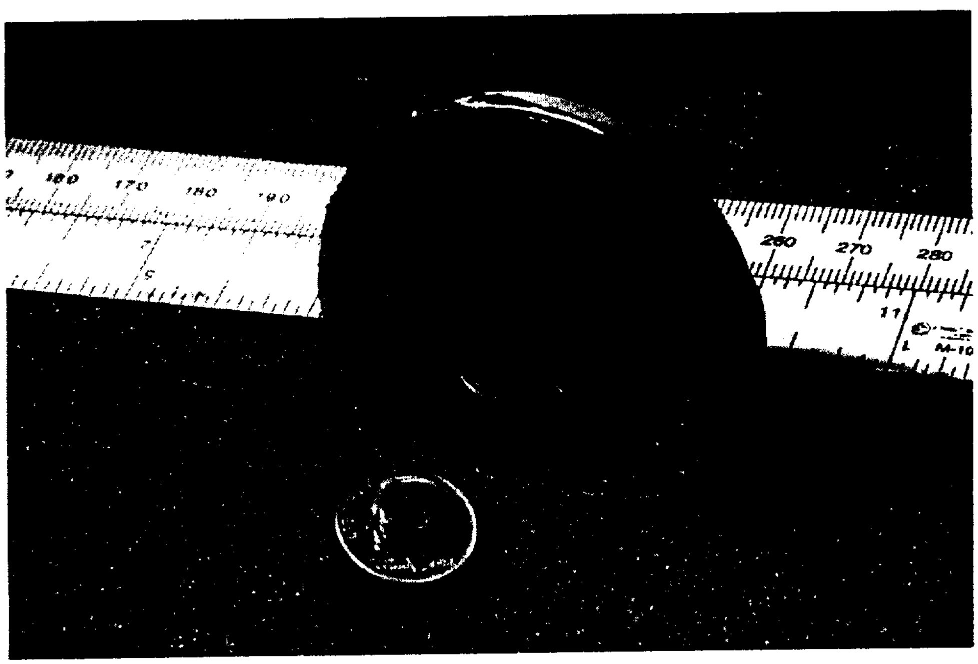

Photo of a mounted, 6-layer (three lattice) infrared bandpass filter designed for operation at 38 microns, as described in the text.

Table of Contents

I. Program Objectives

The program "Nanotechnology Infrared Optics for Astronomy Missions" will design and develop new, nanotechnology techniques for infrared optical devices suitable for use in NASA space missions. The proposal combines expertise from the Smithsonian Astrophysical Observatory, the Naval Research Laboratory, the Goddard Space Flight Center, and the Physics Department at the Queen Mary and Westfield College in London, now relocated to the University of Cardiff, Cardiff, Wales. The method uses individually tailored metal grids and layered stacks of metal mesh grids, both inductive (free-standing) and capacitive (substrate-mounted), to produce various kinds of filters.

The program has the following goals:

1) Model FIR filter properties using electric-circuit analogs and near-field, EM diffraction calculations;

2) Prototype fabrication of meshes on various substrates, with various materials, and of various dimensions;

3) Test filter prototypes and iterate with the modeling programs;

4) Travel to related sites, including trips to Washington, D.C. (location of NRL and GSFC), London (location of QMW), Cardiff, Wales, and Rome (location of ISO PMS project headquarters);

5) Produce ancillary science, including both publication of testing on mesh performance and infrared astronomical science.

II. Progress Report

As of the preparation of this annual report in February 2003, we are pleased to report that we have achieved success in all of the program goals, and have successfully fabricated a 6-layer, 3-stack infrared filter that works nearly exactly according to design at 38 μm.

We have presented our successful work at the January meeting of the AAS in Seattle, and we have submitted for publication to *Applied Physics Letters* an article on the process. The two appendices contain all the details pertinent to these results. We have also presented our work to the SOFIA Science Team with the hope of using these filters on SOFIA instrumentation. An article on our new process is scheduled to appear in the June *Laser Focus World* magazine. We can summarize our achievements as follows:

A. Mesh Modeling

We have used the "MicroStripes" code (Flomerics, Inc.) to perform full-, near- and far-field diffraction modeling of metal mesh performance on substrates. Our "Miles Code" software, which approximates the full calculation in a quick, gui-based window, is useful as an iterative device by adjusting the input parameters (index of refraction, thickness, etc.) to provide agreement with the full calculation. However, despite the somewhat extravagant claims by the MicroStripes manufacturer, this code is also not perfect because numerous free parameters must be set. Key among these, as identified in our earlier papers and proposal documents, is the high frequency (i.e., far IR) character of the real and imaginary parts of the index of refraction of the metal mesh, the high frequency character of the real and imaginary parts of the index of refraction of the <u>substrate</u>, and the character of the interface between the mesh and the substrate material, and in particular the suppression (or possible enhancement) of surface effects at the interface.

B. Filter Fabrication

After numerous sample fabrication and tests, we fabricated a multi-layer preliminary sample FILTER by hand, here at the Smithsonian Astrophysical Observatory X-Ray Laboratory. This sample was measured, and from that we determined that our modeling and our fabrication was on solid ground. We then proceeded to fabricate a monolithic filter, as described in the attached appendices.

C. Staff and Equipment Changes

Dr. Ken Stewart of the NASA Goddard Space Flight Center has joined the team, and has been hired by the Naval Research Laboratory's Remote Sensing Division. The Bruker IFS66v Mid and Far Infrared Fourier Transform Spectrometer is now operational at NRL, and we have obtained both warm and cold sample measurements.

We are excited to report that Dr. Oren Sternberg was a postdoctoral scientist at Smithsonian Astrophysical Observatory, supported by this grant, during the fall of 2002. He has moved to a more permanent position with Jackie Fischer and Ken Stewart at the NRL. He is an expert on the MicroStripes modeling of these filters, on metal mesh properties, and on the filter processes in general.

D. Other Programmatic Matters

During this past year we have held a series of team meetings in DC and talks with our collaborators at the University of Cardiff in Cardiff, Wales. We also attended the AAS meeting.

III. Program Plans

This marks the third and final year of the project and its full success. There remain a few items outstanding, and we therefore are requesting a no-cost extension of one year to bring these to closure. These include, for example, the publication of the results in a scientific journal (paper submitted and currently in review). Some modest additional travel is anticipated in conjunction with this as well.

Appendix A

"Designed Infrared Filters from Nanotechnology Fabrication of Stacked Metal Lattices"

Designer infrared filters from nanotechnology fabrication of stacked metal lattices

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(Submitted to *Applied Physics Letters*, December, 2002)

Abstract:

We have successfully designed and fabricated infrared filters for wavelengths $\geq 15\mu m$. Unlike conventional filters, these consist of stacked metal grids whose geometries and spacings are very much less than a wavelength. The individual lattice layers are assembled using nanoelectronics techniques from gold on polyimide spacers; they resemble some metallic photonic band gap (MPBG) structures. We successfully modeled these filters, including the coupling of near-field electromagnetic modes, after iterative adjustments for material properties. The geometrical parameters are easily altered, allowing for the production of tuned infrared filters with predictable and useful transmission characteristics. Although developed for astronomical instrumentation, the filters are broadly applicable in systems across infrared and terahertz bands.

Infrared filters are used to help define precisely the wavelength response of instruments, and should have sharply defined spectral shapes with high in-band transmission (or blocking in the case of band blocking devices) and excellent rejection outside the bands of interest. Cryogenic operation is essential in the infrared to suppress self-emission, and filters must be able to withstand cryogenic cycling without deterioration. Filters can be made, in rough analogy with optical dielectric filters, by assembling partially reflective layers in quarter-wavelength-spaced dielectric stacks. In practice, however, dielectric stacking is difficult in the infrared because of the limited range of indices of refraction in infrared transmitting materials, the difficulty of working with some of the exotic dielectric materials that are available, and the problematic stability of thick stacks of quarter-wave spaced dielectrics under conditions of cryogenic cycling or long-term exposure to moisture.

A pioneering alternative design for these layers was investigated by Ulrich[1], who used metal mesh grids made of wires or crosses. Such grids typically come in two forms, labeled according to their electromagnetic transmission line theory analogs: inductive meshes, which can be free-standing and are typically formed from an orthogonal pattern of narrow wires, and capacitive meshes, which are the geometric inverse of inductive meshes and, as a result, are a series of metal squares which must be supported by a substrate material. Simple cross-shaped structures, dubbed "resonant crosses" because they are geometrically and electrically analogous to the superposition of inductive and capacitive grids, can also be either free-standing ("inductive") or not ("capacitive") in nature[2-3]. Ulrich's designs have been successfully developed and incorporated into submillimeter and far infrared filters[4-5], which typically have layer spacings of

tens of microns or more, and can be assembled by hand. Metallic photonic band gap (MPBG) structures – periodic metallic structures producing frequency regions in which electromagnetic waves cannot propagate – possess some similar mechanical and electromagnetic properties[6-7].

There are at least three challenges to the task of extending the capabilities of submillimeter mesh filters to shorter wavelengths, while improving their performance and obtaining high fabrication-run yields: identify ways of precisely spacing the thin layers without introducing excessively absorbent materials; perfect the actual fabrication steps, including the alignment control between layers; and develop computer models that accurately predict the final products so that expensive mistakes can be avoided. By taking advantage of new computational and manufacturing techniques, we have achieved reasonable successes in all these areas, and to date we have made filters for the 30μm band using gold lattices photo-lithographically deposited onto layered polyimide stacks.

The filter design for a 38μm band pass filter is shown schematically in Figure 1. It consists of six layers: polyimide, inductive gold crosses, polyimide, capacitive gold squares, polyimide, and inductive gold crosses. The inductive crosses are apertures with periodicity g=22μm, and cross-arm-length (g-2a) of 12.8μm, while the capacitive (filled) squares have the same periodicity, and sides 9.2μm long. The layers are spaced at about $\lambda/30$ using polyimide, resulting in a total filter thickness of about 4μm. These thin layers are much smaller than the spacings used, for example, in some MPBG devices[6], with one important benefit being the relatively high transmission in the short wavelength passband.

The basic transmission line analog for mesh filters developed by Ulrich has been extended[8-10] to address the issues of electromagnetic wave coupling in the limit when the conductive layers are in the near field, and is described more completely by Sternberg[11]. Although the transmission line analog remains useful even at the fractional-wavelength separations we use, the coefficients in the expression for the transmittance become sensitive parameters of the design and must be recalculated for each geometry. Our design was developed using the Micro-Stripes Program[8], which we tested and then modified with physical parameters based on comparisons with preparatory laboratory samples and prototype filters. Figure 2 shows the Micro-Stripes results when a polarized field is propagated through the filter. The figure shows both the currents in the metal, and the field strengths and directions on resonance (frequency of 7.78THz) where the transmission peaks near 70%. The figure illustrate how the spaced metal layers are induced to produce strong surface currents that reflect the off-resonance radiation, while on-resonance radiation (the resonance FWHM $\approx 5\mu m$) is transmitted. The good agreement between our models and laboratory samples (Figure 3) gives us confidence that these effects are physical and the models can be reliably modified. By tailoring the geometries of the lattices and their spacings using these modeling insights, we can tune the final filter's transmission characteristics. One drawback to the current model algorithm is its inability to calculate for wavelengths shorter than the periodicity, which for our 38μm filter is 22μm.

The filters were made in the Naval Research Laboratory's Nanoelectronics Processing Facility, and all dimensions were made to better than ±0.1μm. Initially a <100> oriented N-type polished

silicon wafer was cleaned and oxidized. (The oxide layer is a sacrificial layer to aid with the removal of the filter element from the wafer at the end of the processing.) A thin layer (about 1μm) of polyimide (HD Microsystems PI-2611) was placed onto the surface by a spin coating process and then cured; control of the spin speed and cure cycle provides a way of reproducing films of a uniform thickness. Chrome (about 10 nm, for adhesion) and gold (100 nm) films were then deposited onto the surface by metal evaporation. Optical lithography and wet chemical etching was used to define the pattern into the metal film. The sequence of polyimide coating, metal evaporation and optical lithographic pattern definition were repeated two more times to build up a stack of three filter elements. Optical lithography makes it possible to etch a different pattern in each metal layer and to accurately and precisely align the new layer to the previous metal layer. In principle many more than three metal lattices can be laid down with this method. The final step was the removal of the layered filter from the silicon wafer by immersion in a dilute HF bath. Figure 4 shows a photograph of the filter after removal from the wafer. The actual fabrication of the filter is an advancement over the stages originally pioneered for the development of free-standing metal grids for use in the infrared as Fabry-Perot etalons[12-14].

The 38 μm filter was measured at the NASA Goddard Space Flight Center with a Bruker Fourier Transform Spectrometer; Figure 3 shows the measured, resultant transmission, with the Micro-Stripes modeled filter shape superimposed. The agreement is very good (index of refraction of polyimide of 1.65). Several samples from this fabrication run had double transmission peaks, or secondary transmission maxima, on the wings of the main feature; some weak residuals of these may be seen in Figure 3. These secondary bumps may be due to measurement or mounting

errors, or to fabrication irregularities at some stage in the processing, and further investigation is underway. There is one uniform, second order disagreement with the model: the measured filter transmission has a long wavelength tail beyond 45μm considerable higher than the model predicts, and this disagreement is currently under study.

The most significant conclusion to be drawn from this work is that the transmission line modeling is reliable, and the general fabrication techniques are in hand and can be used with some confidence to make infrared filters with a wide range of designed properties: narrow band, cut-on or cutoff filters, beamsplitters, or other devices. A simple scaling of the mesh geometries and layer spacings allows the shifting of a filter's transmission properties to longer or shorter wavelengths. The primary current limitation is not in the fabrication steps, but rather in the absorption of the polyimide substrates, which at wavelengths below 20μm becomes unacceptably large for use in many designs. We have therefore begun an alternative process using polypropylene films, whose absorption in the infrared is considerably smaller. Our earlier work on free-standing metal grids[12] included techniques for making 3-D metallic structures from similar patterns, and adding a 3-D (photonic crystal-like) capability to the filter design opens further avenues of possibility. Because the adjusted Micro-Stripes Program now provides a very accurate predictor of filter performance, we can tailor the most desirable filter properties by using a variety of alternative geometrical designs and parameters, coupled with a more complex system of stacked layers[11]. We have already designed innovative infrared filters with very steep cut ons, >40dB/μm, and simple narrow bandpass filters with $\Delta\lambda/\lambda \approx 5\%$ and good out-of-band blocking. Thanks to modern computational tools and fabrication technologies, a powerful new class of mid

and far infrared optics can be designed at low cost for the particular needs of individual instruments or measurements.

We acknowledge many helpful interactions with our colleagues J. Fischer, K. Stewart and B. Hicks of NRL. M. Greenhouse was an early enthusiast for this design, and we are grateful for his contributions. H. Moseley made available to us the Micro-Stripes Program, and R. Henry did the filter measurements. J. Miles produced an early version of the transmission line theory code which was used to assist with the Micro-Stripes modeling. The first filter made with this general process was hand assembled at the Smithsonian Astrophysical Observatory's X-Ray Laboratory by D. Goddard, and his efforts helped to give us the confidence to proceed with the monolithic processing described here. The program was supported in part by NASA grant NAG5-7394.

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Figure Captions

Figure 1: Schematic drawing of the 38μm filter structure (polyimide spacers not shown). top: 2 layers, with inductive gold crosses below (green) and capacitive squares above (red). The crosses have periodicities of 22μm, cross arm-widths of 3.5μm, and arm-to-arm separations of 9.2μm [in conventional notation: g=22μm, 2a=9.2μm, 2b= 3.5μm]. The squares have periodicities of 22μm, and separations of 3.5μm [conventional notation: g=22μm, 2a=3.5μm]. bottom: the 3 layer structure, with the third layer of inductive gold crosses in dark green, and first two layers visible. Precise alignment of the patterns (± 0.1μm) is essential.

Figures 2: The relative surface currents and electric fields on the front of the first metal surface of the 38μm filter; calculated on-resonance at a frequency of 7.79THz, and with polarized incident radiation. The difference between the light green and dark blue currents is about 15dB; the largest surface currents (obtained off-resonance) are about 15dB stronger than these.

Figure 3: Measured and modeled transmission for the 38μm filter. The secondary peak at 27μm is well modeled, and is the result of the polyimide layer; the secondary peak at 45μm, and the transmission tail longward of it, are not well modeled, and their origins are currently under investigation.

Figure 4: Photograph of the 38μm filter film before mounting. The sample was fabricated on a 3" silicon wafer.

Appendix A

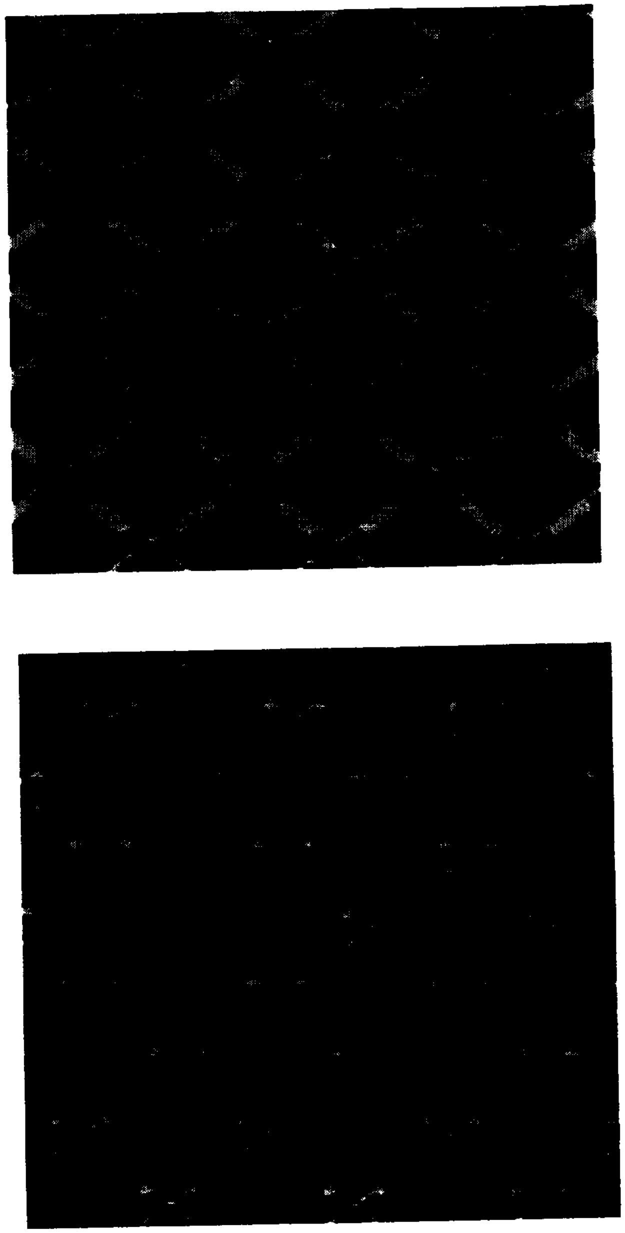


Figure 1

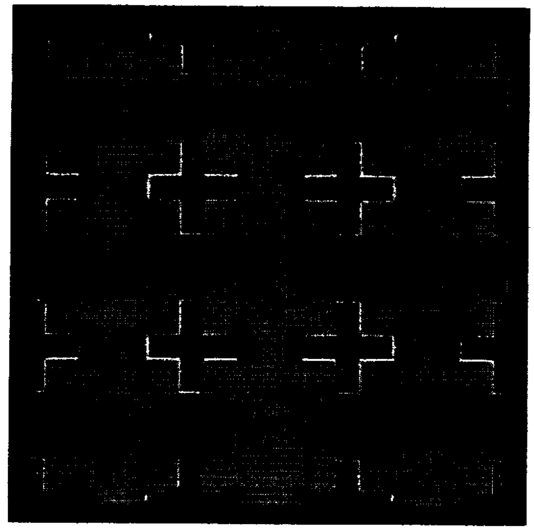


Figure 2

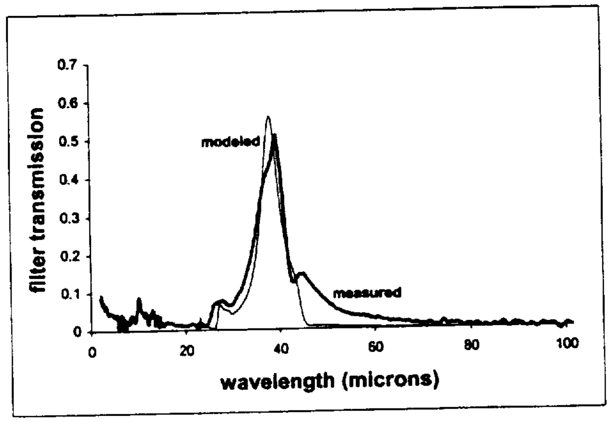

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
filter transmission
modeled
measured
0
20
40
60
80
100
wavelength (microns)

Figure 3

Figure 4

Appendix B

Bulletin of the American Astronomical Society Presentation

Designer Infrared Filters: A New, Nanotechnology Process to Make Precise IR Filters using Layered Metal Meshes

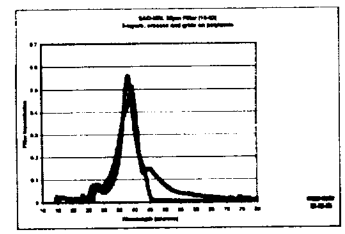
Appendix B

Howard A. Smith and O. Sternberg (CfA), M. Rebbert, J. Fischer, K. Stewart, B. Hicks (NRL), M. Greenhouse, and R. Henry (GSFC)

Introduction

We have developed a method of fashioning infrared optics, including band-pass and narrow-band filters, and wavelength-specific cut-on and cutoff filters, for use at wavelength as short as about 15um. The optical elements consist of precisely aligned and layered stacks of metal lattices embedded in plastic, each lattice formed of periodic geometrical patterns designed and spaced for particular infrared applications. We are able to model, with reasonable success, the near-field electromagnetic modes across the metallic boundaries, and to take advantage of their couplings to tailor the transmission in these devices using spacings and geometries with dimensions very much smaller than a wavelength, in contrast with more conventional, quarter-wavelength spaced filters. We use methods of nanotechnology and photolithography to fabricate the elements from 2-D gold lattices on polyimide or polypropylene, and 3-D structures may be possible. The optical product is a film with precise transmission characteristics, as well as excellent cryogenic and handling properties. These infrared filters are analogous to submillimeter and millimeter wave filters that use metallic grids of much larger dimensions. Although developed for use in astronomical instrumentation, such filters are broadly applicable. We present the results of computer simulations, fabrication runs, and laboratory measurements.

Photo of the 38um filter film before mounting. Sample was fabricated on a 3" silicon wafer.



Measured (red) and modeled (green) transmission of the 38um filter.

Background

Mid- and far-infrared (here used to designate wavelengths from approximately 10 um to about 300 um) filters are used to help define precisely the wavelength range of response of infrared instruments. Desirable optical qualities include high, flat transmission, sharply defined spectral shapes, and excellent out-of-band rejection; cryogenic operation is essential to suppress self-emission. The need for improved infrared filter performance is increasing as new, larger-format, sensitive infrared detector arrays become available. Narrow band filters, for example, having band passes of a few to tens of percent, could act as single-line selection filters for lower spectral resolution imaging instruments, or order -sorting filters for high resolution Fabry-Perot or grating systems. Narrow-band filters, optimized for specific emission lines, can facilitate high spatial resolution line imaging while reducing the continuum background and minimizing confusion from adjacent lines. Spectrally selective beamsplitters are also important, because they can permit high performance, multi-wavelength instruments to observe simultaneously. Stacks of dielectric layers work well at shorter wavelengths, but fail in the FIR because of the limited range of indices, the difficulty of working with exotic materials, and the problematic stability of thick stacks of 1/4-wave spaced layers under conditions of cryogenic cycling or long-term exposure to moisture.

A pioneering alternative design for these layers was investigated by Ulrich (1), who used metal mesh grids made of wires or crosses. Such grids typically come in two forms, labeled according to their electromagnetic transmission line theory analogs: inductive meshes, which can be free-standing and are typically formed from an orthogonal pattern of narrow wires, and capacitive meshes, which are the geometric inverse of inductive meshes and, as a result, are a series of metal squares which must be supported by a substrate material such as polyimide film. Simple cross-shaped structures, dubbed "resonant crosses" because they are geometrically and electrically analogous to the superposition of inductive and capacitive grids, can also be either free-standing ("inductive") or not ("capacitive") in nature. Figure 1 defines the geometries. The method is analogous to that used in sub-millimeter filters (2).

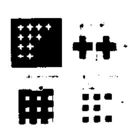


Figure 1: Inductive and capacitive geometries for grids and resonant crosses.

New Filters: The Challenges

There are at least four challenges to fabricating improved infrared filters:

(1) improving spectral performance, while obtaining reliable processing and high yields;
(2) identify ways of precisely spacing the thin layers without introducing excessively absorbption;
(3) perfect the actual fabrication steps, including the alignment control between layers;
(4) develop computer models that accurately predict the final products.

We have achieved reasonable successes in all these areas , and to date we have made filters for the 30 um band, and have modeled and fabricated a bandpass filter centered at 38um using gold lattices photo-lithographically deposited onto layered polyimide stacks.

Figure 2: Design of the current, 3-layer 38um filter: inductive crosses, capacitive grids, and inductive crosses. Top: two of the layers; below: the set of three layers. The layers are spaced by ~lambda/30 thicknesses of polyimide (not shown).

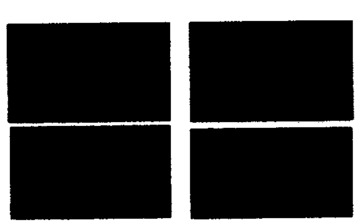


Figure 3: The surface currents in the metal, and the electric fields, at the position of the first metal surface. Left: off resonance; right: on resonance. Calculations by the MicroStripes program.

The Solutions

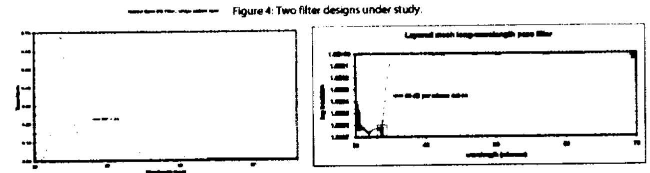
FABRICATION : The current 38um filter design is shown schematically in Figure 2. It consists of six layers: polyimide, inductive gold crosses, polyimide, capacitive gold squares, polyimide, and inductive gold crosses. The inductive crosses are apertures with periodicity g=22 um, and cross-arm-length (g-2a) of 12.8 um, while the capacitive (filled) squares have the same periodicity, and sides 8.7 um long. The layers are spaced at about lambda/30 using polyimide, resulting in a total filter thickness of about 4 um. Figure 2 shows the two-layer and then the three-layer stack (the polyimide is omitted for clarity).

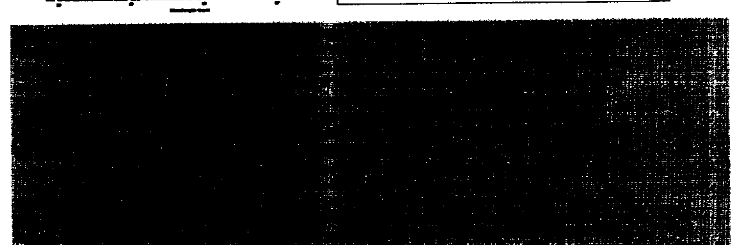
The filters were made in the NRL Nanotechnology Branch Facilities (all dimension to better than about 0.1um), and were measured at NASA GSFC. The figure above shows the measured, resultant transmission (room temperature), with the modeled filter shape superimposed. The agreement is very good (index of refraction of polyimide of 1.65). Our measurements found a number of samples from this fabrication run with double peaks or secondary transmission maxima on the wings of the main feature. Some variants of these may be seen in the figure above. These secondary bumps may be due to measurement or mounting errors, or to fabrication irregularities at some stage in the processing, and further investigation is underway. There is one uniform, second order disagreement with the model: the current filter transmission has a long wavelength tail considerable higher than the model predicts, and this disagreement is currently under study.

COMPUTER DESIGN : The design was done with the MicroStripes Program (Flomerics, Inc.). To use it, we had to modify the inputs with physical parameters obtained from preliminary laboratory sample filters. Although an transmission line analog remains applicable even at the fractional-wavelength separations we use, the coefficients in the expression for the transmittance become sensitive parameters of the design and so must be recalculated for each design. Figure 3 shows the Micro Stripes predictions when a polarized field is propagated through the filter. The figures show both the currents in the metal, and the field strengths and directions, at two frequencies: far from resonance (1.8THz, where the transmission is below .01%), and on resonance (7.79THz, where the transmission peaks near 70%). The figures illustrate how the spaced metal layers are induced to produce strong surface currents that reflect the off-resonance radiation, while on resonance radiation (the resonance FWHM ~5um) is transmitted. The good agreement between our models and laboratory samples gives us reasonable confidence that these dominant effects are physical. By tailoring the geometries of the lattices and their spacings using these modeling insights, we can tune a filter's transmission characteristics.

Future Work

Figure 4: Two filter designs under study.





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